

Maxwell's paper on the electromagnetic field has been regarded as his greatest contribution to electrical science. This article, marking the centenary of its publication, describes how the concept of electromagnetic waves evolved. The author is Director of the Radio Research Station, DSIR.

MAXWELL'S ELECTROMAGNETIC WAVES

—some thoughts on a centenary

J. A. RATCLIFFE, C.B.E., M.A., F.R.S., M.I.E.E.

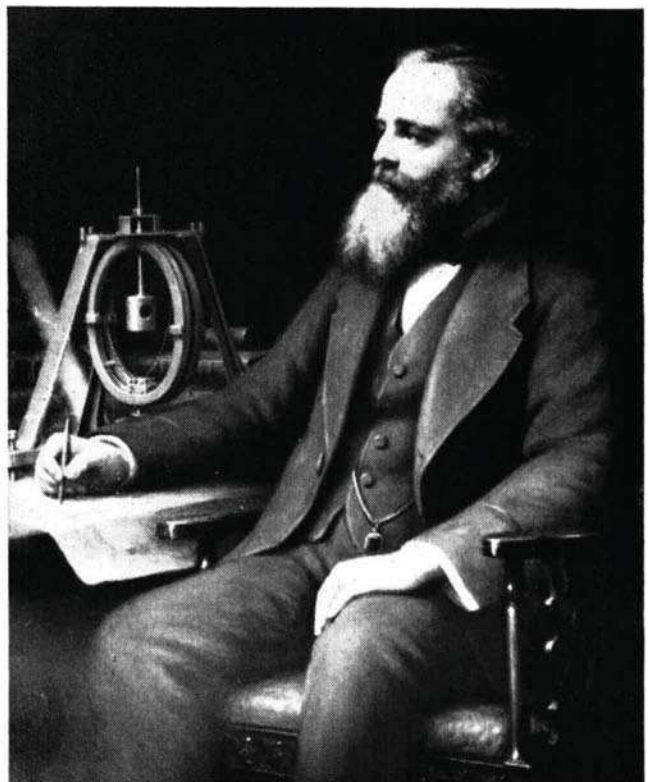
On the 8th December 1864, Maxwell read before the Royal Society his famous paper entitled 'A dynamical theory of the electromagnetic field'.

As seen from the present day, the most interesting step in this paper is the introduction of the idea that a potential difference applied across a pure dielectric can polarise it and produce an 'electric displacement'. He writes:

'In a dielectric under the action of electromotive force, we may conceive that the electricity in each molecule is so displaced that one side is rendered positively and the other negatively electrical, but that the electricity remains entirely connected with the molecule, and does not pass from one molecule to another. The effect of this action on the whole dielectric mass is to produce a general displacement of electricity in a certain direction. This displacement does not amount to a current, because when it has attained to a certain value it remains constant. Here, then, we perceive another effect of electromotive force, namely, electric displacement, which according to our theory is a kind of elastic yielding to the action of the force, similar to that which takes place in structures and machines owing to the want of perfect rigidity of the connexions.'

He then writes down equations to express 'the relation between electric displacement, true conduction, and the total current, compounded of both'.

James Clerk Maxwell from the portrait by R. N. Campbell. This posthumous portrait, painted in 1929, hangs in the Maxwell Room at Savoy Place



Later he adds equations to express

- the relation between the lines of magnetic force and the inductive coefficients of a circuit, as already deduced from the laws of induction
- the relation between the strength of a current and its magnetic effects, according to the electromagnetic system of measurement

- the value of the electromotive force in a body, as arising from the motion of the body in the field, the alteration of the field itself, and the variation of electric potential from one part of the field to another
- the relation between electric displacement, and the electromotive force which produces it

- the relation between an electric current, and the electromotive force which produces it
- the relation between the amount of free electricity at any point, and the electric displacements in the neighbourhood
- the relation between the increase or diminution of free electricity and the electric currents in the neighbourhood

Ratio e.m.u./e.s.u.

He then continues:

'The general equations are next applied to the case of a magnetic disturbance propagated through a non-conducting field, and it is shown that the only disturbances which can be so propagated are those which are transverse to the direction of propagation, and that the velocity of propagation is the velocity v , found from experiments such as those of Weber, which expresses the number of electrostatic units of electricity which are contained in one electromagnetic unit.

'This velocity is so nearly that of light, that it seems we have strong reason to conclude that light itself (including radiant heat, and other radiations if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws. If so, the agreement between the elasticity of the medium as calculated from the rapid alternations of luminous vibrations, and as found by the slow processes of electrical experiments, shows how perfect and regular the elastic properties of the medium must be when not encumbered with any matter denser than air. If the same character of the elasticity is retained in dense transparent bodies, it appears that the square of the index of refraction is equal to the product of the specific dielectric capacity and the specific magnetic capacity. Conducting media are shown to absorb such radiations rapidly, and therefore to be generally opaque.'

The mathematical formulation follows; it occupies only two pages and is closely similar to what is found in present-day textbooks. Indeed, it is quite remarkable how little the formal mathematical expression of Maxwell's equations and the method of their solution has altered during the last 100 years.

Vortex tubes and idler spheres

This remarkable theory might seem to have evolved in Maxwell's mind

through the processes of logical reasoning so clearly stated in his paper. However, three papers which he had published previously in the *Philosophical Magazine* show how his ideas about electromagnetic fields had developed. In these he attempted to formulate, with mathematical precision, a model of Faraday's magnetic

seems to have realised that, if this displacement idea were incorporated from the beginning, the theory could be restated without recourse to the complicated vortex model. This is what he did in the paper of 1864. The mechanical picture had led him to his final conclusion, but he realised it was no more than a

Faraday. Life II 282.

I am more inclined to the notion that in the transmission of the (magnetic) force there is such an action (via intermediate agency) than that the effects are merely attraction and repulsion at a distance. Such an affection may be a function of the ether, for it is not at all unlikely that if there be an ether it should have other uses than simply the conveyance of radiations

Isolated jotting from one of Maxwell's notebooks

Three notebooks, concerned mainly with examination questions, are in the possession of King's College, London, by whose kind permission this extract is reproduced. Maxwell was Professor of Natural Philosophy and Astronomy at King's College from 1860 to 1865

lines of force. He saw that these lines must be supposed to be in tension and to exert a pressure sideways—which is just what they would do if they were tubular vortices spinning about their axes. He then suggested that, at the interfaces of the vortices in a system of this kind, there would be rotating elements revolving in the opposite direction, 'idler elements' as he called them. He showed that, if these were considered to be analogous to the electricity in the medium, the phenomenon of electromagnetic induction could be explained.

In order to account for the phenomenon of electric displacement, the electric particles (his 'idler elements') must be under the control of elastic forces in the vortex tubes against which they rest, and if these elastic forces exist it will be possible to propagate a wave through the medium. He calculated the velocity of such a wave and showed how it was related to the results of electrical measurements.

At this stage Maxwell apparently decided to drop the complicated picture of cylindrical vortices with 'idler spheres' rotating between them. They had led him to the idea of electric displacement, and he now

fictional analogy, and he was content to drop it when he had fully appreciated its significance. In his own words:

'I do not bring it forward as a mode of connexion existing in nature, or even as that which I would willingly assent to as an electrical hypothesis. It is, however, a mode of connexion which is mechanically conceivable, and easily investigated, and it serves to bring out the actual mechanical connexions between the known electromagnetic phenomena; so that I venture to say that any one who understands the provisional and temporary character of this hypothesis, will find himself rather helped than hindered by it in his search after the true interpretation of the phenomena.'

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